SUSPENDED SEDIMENT CONCENTRATION AND DISCHARGE RELATIONSHIPS IN THE ETHIOPIAN HIGHLANDS

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ABSTRACT

This study presents a basic investigation on the influence of discharge on the variable sediment concentrations in the Andit Tid, Anjeni, and Maybar watersheds of northern Ethiopia. With valuable sediment concentration and stage measurements recorded by the Soil Conservation Research Programme at monitoring sites starting in the 1980's, it is possible to gain knowledge about the important processes that affect changing sediment concentrations. For the years of observation, sediment yield estimates were 5.4 $t{\cdot}ha^{-1}y^{-1}$, 22.5 $t{\cdot}ha^{-1}y^{-1}$, and 8.8 $t{\cdot}ha^{-1}y^{-1}$ for Andit Tid, Anjeni, and Maybar respectively. Although catchments tend to exhibit positive correlation between runoff and sediment concentration, albeit with a degree of scatter, these catchments exhibit a peculiar scatter of observations with high concentrations for low flows and low concentrations for high flows. Due to this behavior, a sediment rating curve for all observations was unsatisfactory and subsequently, using several cumulative precipitation divisions to group related observations, non-linear regression showed a weak correlation for the Andit Tid basin, for most of the Anjeni basin and during the early portion of the rainy season in the Maybar basin. Stratification of points into cumulative precipitation ranges served to bring some order to the scatter plots of sediment concentration versus discharge to demonstrate that higher concentrations are observed during the beginning of the rainy season and lower concentrations are observed towards the end of the rainy season. Still, the exhaustion of available soil for transport may prove to have an important role in limiting the ability of discharge to account for the variability of sediment concentration throughout the season.

BIOGRAPHICAL SKETCH

Jorge Eduardo Guzman and Silvia Gioconda Flores were married in Guayaquil, Ecuador in August 1984. On the 16th day of February 1987, Christian David was born in New York City, New York. The sons and daughters of Jorge Eduardo and Silvia were Christopher Lionel, Christian David, Silvia Diane, and Sophia Gabriella.

In 2005, Christian graduated from Gateway High School in Kissimmee, Florida and commenced his undergraduate studies at the University of Florida. He graduated with a Bachelor of Science in Agricultural and Biological Engineering, specializing in Land and Water Resources Engineering with a minor in French.

Beginning in August 2009, Christian was awarded a State University of New York (SUNY) Fellowship and research assistantship to pursue an MS/PhD in Soil and Water Engineering at Cornell University. His passions outside of academia are dancing salsa, going to the beach, playing soccer, riding his bike, reading the bible, spending time with his family, eating oranges, and sketching.

This thesis is dedicated to my father Jorge Eduardo for all his hard work and the passion he has for his family and the Lord, and to my wonderful mother Silvia for her warmth and the happiness she brings to my life.

ACKNOWLEDGMENTS

I would like to thank all my classmates and colleagues in the Soil and Water Lab for welcoming me to Ithaca and helping me adjust to the new environment. I would also like to express my great appreciation for Professor Tammo Steenhuis and the insight, guidance, and support he has generously given. Furthermore, I am grateful to Professor J-Yves Parlange for all his assistance.

The hydrological and sediment data were made available through the Amhara Regional Agricultural Research Institute (ARARI) and special assistance on this project was provided by the faculty and staff of Bahir Dar University. I thank Assefa Derebe and Birru Yitaferu of ARARI for their support. I would also like to recognize the head of the School of Civil and Water Resources Engineering, Mr. Mengiste Abate, as well as Mr. Seifu Admassu, Dr. Birhanu Zemadim and Dr. Amy Collick for all their help and hospitality during my visit to Bahir Dar University. Recognition is also due to the initiators of the Soil Conservation Research Programme (SCRP) and their local research assistants who had the dedication, day and night, to collect data in all conditions of weather.

Finally, I thank the Lord for all the love He has given. "The Lord is my strength and my shield; my heart trusted in him, and I am helped: therefore my heart greatly rejoiceth; and with my song will I praise him." Psalm 28:7

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SUSPENDED SEDIMENT CONCENTRATION AND DISCHARGE RELATIONSHIPS IN THE ETHIOPIAN HIGHLANDS

1. INTRODUCTION

Food systems around the world are being threatened by soil degradation while perpetuating the conditions that foster erosion. Every year in Ethiopia, fertile land flows away from agricultural plots into rivers and lakes, causing concerns for local residents and increasing hindrances for national agricultural aspirations. The siltation of rainwater harvesting reservoirs and hydro-electric power dams thwarts attempts to improve access to drinking water and leads economic investments to inefficiently function, as storage capacity is lost (Tamene et al 2007). Scientists, engineers, and experts recognize the benefits of developing models to simulate and predict future soil loss as evinced by numerous attempts to apply SWAT, AGNPS, and USLE equations to the Ethiopian highland conditions. Significant work has also been done to determine how raindrop-impact (Hairsine and Rose 1991, Parlange et al 1999) and stream power (Siepel et al 2002) influence rates of erosion. Suspended sediment concentration has been studied against stream flow, for example with rating curves, to determine if relationships exist that characterize basin responses to storm events. These relationships can be used to provide a continuous record of estimated values where direct measurement is not possible or too expensive. For instance, such relationships have been investigated in a variety of conditions and countries namely: the humid continental United States (Putnam and Pope 2003), semi-arid watersheds in Israel (Powell et al 1996, Alexandrov et al 2003), deciduous forest watersheds in Iran (Sadeghi and Saeidi 2010), the desert streams in India (Sharma 1984), a suburban tropical basin in Zaire (Lootens and Lumbu 1986), and a subtropical catchment in

South China (diCenzo and Luk 1997). Whereas sediment concentration is generally found to increase with discharge, significant scatter can reveal that this trend is being interrupted by other processes, i.e. tillage activity (Nyssen et al 2000). Efforts to understand which processes cause poor correlations for sediment rating curves are essential if progress toward the establishment of effective agricultural practices is to be made. Such practices would enhance the capacity to feed people without threatening future food production, water quality, and energy investments.

The Soil Conservation Research Programme (SCRP), initiated in the 1980s by the Ethiopian Ministry of Agriculture and the Swiss Agency for Development and Cooperation (SDC), has accumulated excellent hydrological and soil erosion data aimed at reducing on-site and off-site effects of land degradation. Sediment loss estimates have been calculated on individual test plots throughout the watersheds (Bosshart 1997), providing estimates of the quantity of soil that can leave a field during the intense rainy season. Nevertheless, suspended sediment concentrations at catchment outlets may signify a more descriptive trend for soil leaving the entire watershed. While it can be argued that increasing discharge leads to increasing sediment yield, a common assumption is made at the watershed scale: there is a unique relationship between discharge (Q) and suspended sediment concentration (SSC) in which SSC variations are strongly attributed to Q changes. This paper investigates the limited success of sediment rating curves in attempting to define suspended sediment concentration-discharge relationships for SCRP data of three watersheds in the Ethiopian highlands. Vanmaercke et al (2010) found significant scatter is typical of plots between suspended sediment concentration and discharge at catchment outlets when investigating sediment dynamics in semi-arid regions of Ethiopia. Often, this scatter can be improved by stratifying observations into related periods; thus, cumulative rainfall ranges reflecting the changing soil moisture status of the watersheds were used.

With soil and water conservation measures seeking to decrease runoff in order to prevent erosion, it is important to estimate the impact that can be expected from these implemented measures. Thus, the specific objectives of this study are (1) to find the level of influence discharge has on suspended sediment concentration by analysis of generated sediment rating curves, (2) to identify classification groups or time scales that improve rating functions, and (3) to discuss possible processes interfering with the establishment of strong a SSC-Q relationship.

2. METHODS

Sediment concentration, precipitation, and catchment discharge data were collected from research sites established by the Soil Conservation Research Programme (SCRP), an extensive project initiated in the 1980s to help determine methods to counteract land degradation. Funding for the project was provided by the Swiss Agency for Development and Cooperation (SDC). The Ministry of Agriculture of Ethiopia and the Center for Development and Environment (CDE) at the University of Bern administered the project through seven monitoring sites from 1981 to 1998, of which three catchments have been chosen for analysis in this study. The Andit Tid, Anjeni, and Maybar research stations (Figure 1) are located within the Amhara National Regional State, and all have continued to collect hydrological data after the end of the project (Table 1). Agricultural fields are present throughout with many farms employing soil conservation structures to control erosion.

Figure 1: Map of SCRP research stations (ETHIO-GIS 2004)

Table 1: Field Site Information (SCRP 2000a, SCRP 2000b, SCRP 2001, Yohannes 1989, Leggesse 2009, Hurni et al 2005)

	Andit Tid	Anjeni	Maybar
Area (ha)	477.3	113.4	112.8
Location	39°43'E/ 9°48'N	37°31'E/ 10°40'N	39°40'E/ 11°00'N
Years	1989-1996 (8)	1989-1997 (9)	1989-2002 (14)
Mean Annual Rainfall (mm)	1467	1675	1417
Rainfall pattern	bimodal	unimodal	bimodal
Major Soils	Andosols, Fluvisols, Regosols, Lithosols	Alisols, Nitosols, Cambisols	Phaeozems, lithosols, Gleysols
Land in cultivation	15%	90%	60%

Staff were employed by the SCRP (i.e. trained local research assistants) to collect runoff discharge and suspended sediment concentration at the outlet of each catchment. Discharge measurements were monitored through manual stage readings in combination with automatic float gauges. Stage discharge relationships formulated by the SCRP allowed for the calculation of stream flow rates ("q" in L/s) which were used to obtain discharge volumes ("Q", m^3or mm). Henceforth "discharge" will be referred to as a volume unless otherwise specified. River sediment samples were collected every 10 minutes during rainfall events using one liter bottles. The samples were later filtered and oven dried to determine sediment concentration. Although more rigorous sampling methods exist to take into account vertical gradations in concentration, the turbulent flow in such streams permits the assumption that there is sufficient mixing for the sample to be representative of the concentration. Hurni (1984) and Bosshart (1997) discuss in detail the infrastructure for data collection and processing.

Although the collection of sediment concentration and discharge data is quite impressive, it is not without imperfections. In a few instances, river sediment samples were not available due to the rapid onset of flash floods which occurred at very early or late hours of the day. To limit the investigation to the effect of discharge on sediment concentration, values of discharge were only included if a sediment concentration value was available for the same time frame. Thus, the study focuses on storm events that carry sediment and not the remaining discharge which did not have available sediment measurements. Concentration values were recorded at 10 minute intervals during the initial period of the storms and every 30 minutes when water levels decreased (Bosshart 1997); values were considered constant until the next measurement. The total sub-hourly measurements used were 2945, 5354, and 2625 for Andit Tid, Anjeni, and Maybar respectively. Soil loss was calculated from suspended sediment concentration (SSC) using total discharge volume (Q) for the time period. Sub-hourly sediment yield (SY) and discharge measurements were summed over N time steps (varied from day to day), and were used to calculate average daily storm sediment concentration. The same procedure was followed to obtain biweekly and monthly summations from daily storm summations of sediment yield and discharge. All subsequent averages into larger time periods refer to a “per storm basis” based on paired discrete measurements.

$$Q_j = \left(\sum_{i=1}^{N} q_i \cdot \Delta t_i\right)_j \quad ; \quad SY_j = \left(\sum_{i=1}^{N} q_i \cdot \Delta t_i \cdot SSC_i\right)_j \quad ; \quad SSC_j = \frac{SY_j}{Q_j} \qquad (1)$$

Where q_i is the flow rate in L/s, t_i is time in s, Q_j is flow volume in L, SSC_i is suspended sediment concentration in g/L, SY_j is sediment yield in g, and SSC_j is average suspended sediment concentration in g/L.

To understand the changing nature of sediment concentration with respect to the moisture status of the watershed, as well as its progression through the rainy season, cumulative daily rainfall was used to delineate the early, the middle, and the late periods of each season. The starting and ending points for the observed rainy season were determined using the method developed by Lui et al (2008). Furthermore, as discussed by Lui et al, precipitation (P) was defined as effective precipitation, where daily evaporation was subtracted from daily precipitation in an effort to focus on precipitation exclusively available for transport through overland flow, interflow and base flow. These periods were approximated by the following ranges: “P<100mm” and “100mm<P<300mm” representing the early part of the rainy season, “300mm<P<500mm” and “500mm<P<700mm” representing the middle part of the rainy season, and “700mm<P<900mm” and “P>900mm” representing the late part of the rainy season. Nonlinear regressions were fitted to these data to evaluate the relationship between sediment concentration and discharge with sediment rating curves:

$$SSC = a \cdot Q^{b}, \text{ with SSC in g/L and Q in mm} \quad (2)$$

Finally, the three watersheds were plotted against each other for the precipitation ranges of “P<300mm”, “300mm<P<700mm”, and “P>900mm” to evaluate similarities and differences in responses to storm discharge. Within each range, the original precipitation delineations were also represented.

3. Results

Preliminary graphical analysis was the first step in this investigation to avoid misrepresentation and to determine whether a SSC-Q relationship was simple or complex (Glysson 1987). The graphical analysis revealed that further stratification of points may improve the development of rating curves, but that the scatter among these groups indicates complex underlying sediment supply processes.

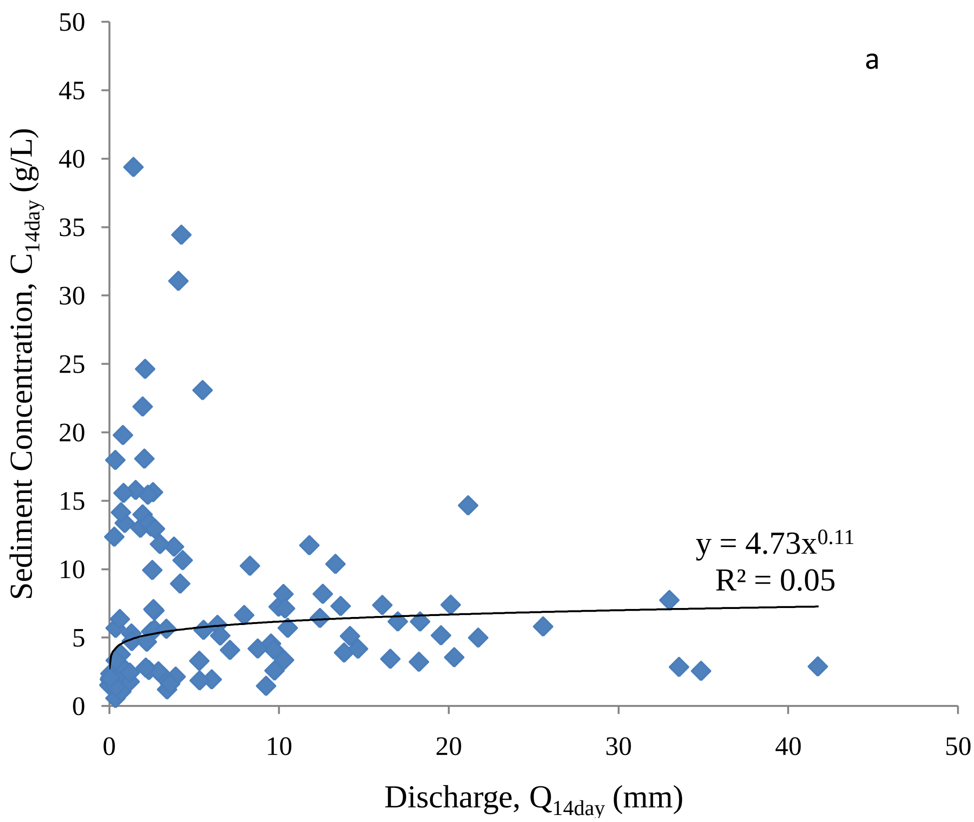
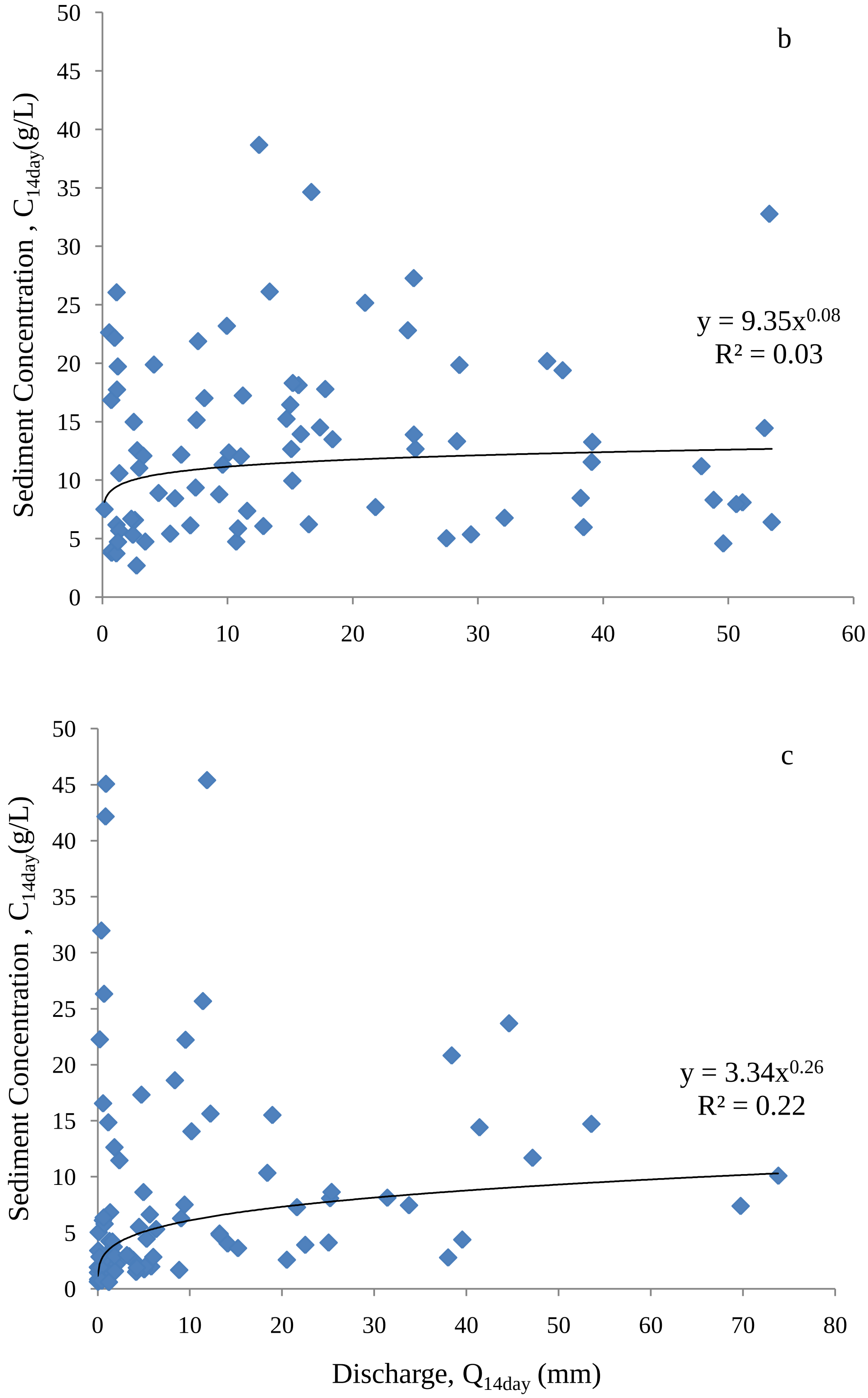


Figure 2. Biweekly Storm Concentration vs Discharge, all observations (a) Andit Tid, (b) Anjeni, (c) Maybar

Figure 2 (Continued)



Compiling the storm values into daily, biweekly, and monthly (Appendix A1-A3, Figure 2) helped to identify the most descriptive time scale for sediment transport dynamics. For the most part, the general shape and characteristics of the SSC-Q plot remained similar. Daily time scales provided an illustration of the initial raw data and avoided most of the hysteretic influence (Figure 3) often associated with concentration-discharge plots (Williams 1989).

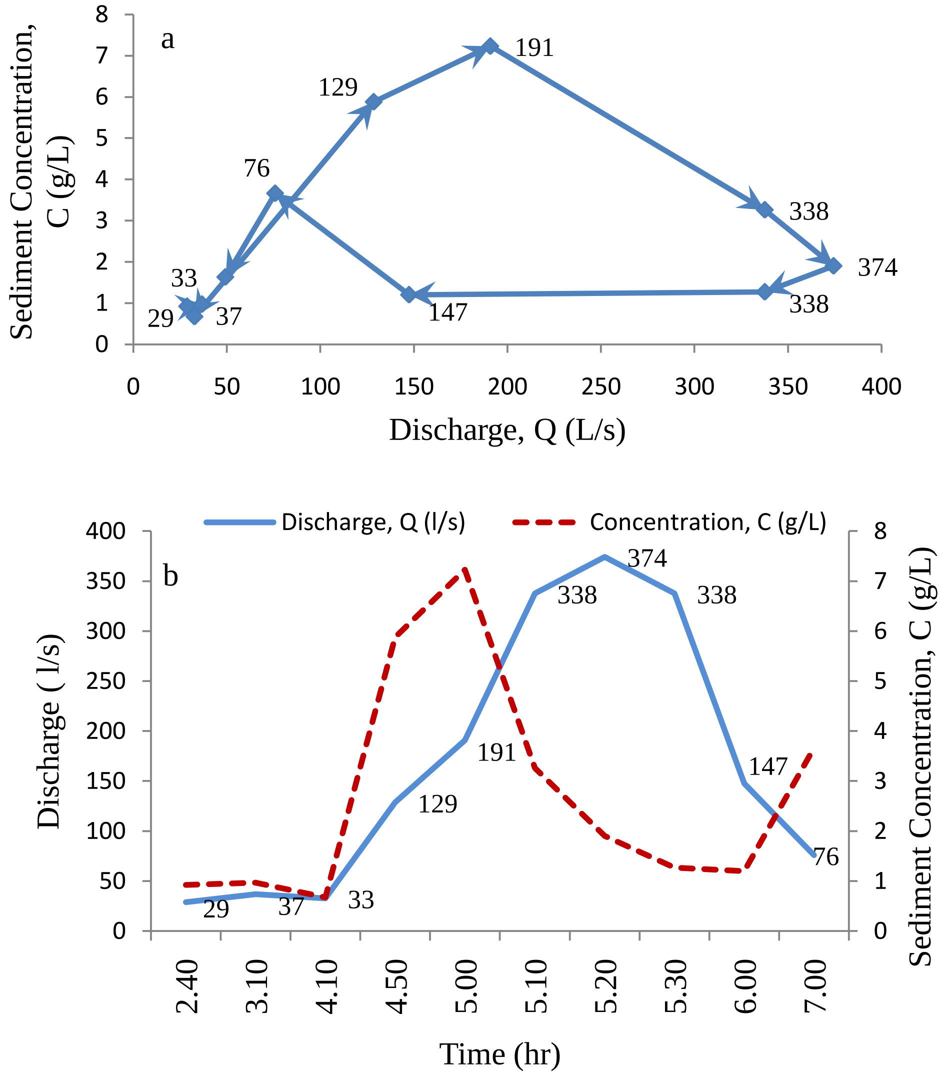


Figure 3. (a) Hysteretic loop at Maybar, 4 August 1989 (b) Concentration and Discharge Peaks, 4 August 1989

For all these time scales, an overall regression did not result in a satisfactory relationship (biweekly shown in Table 2, Figure 2) since the extremities of low flow-high concentration, high flow-low concentration, and low flow-low concentration created three distinct areas that did not correspond to any consistent trend. Usually, logarithmic plots are used, but the resulting scatter was such that no trend could be visually observed. Further analysis used non-transformed representation rather than logarithmic representation in order to draw attention to the distinct values in the graphs. The monthly time scale values summarized general trends in monthly and annual sediment yield (Figure 4); sediment yield estimates were 5.4 $t \cdot ha^{-1}y^{-1}$, 22.5 $t \cdot ha^{-1}y^{-1}$, and 8.8 $t \cdot ha^{-1}y^{-1}$ for Andit Tid, Anjeni, and Maybar respectively. During the larger rainy season in the watersheds, there was a decrease in average monthly sediment concentration. This decrease is less noticeable at the Maybar site, which was likely caused by the more variable year to year fluctuations in precipitation and discharge (Hurni 2005).

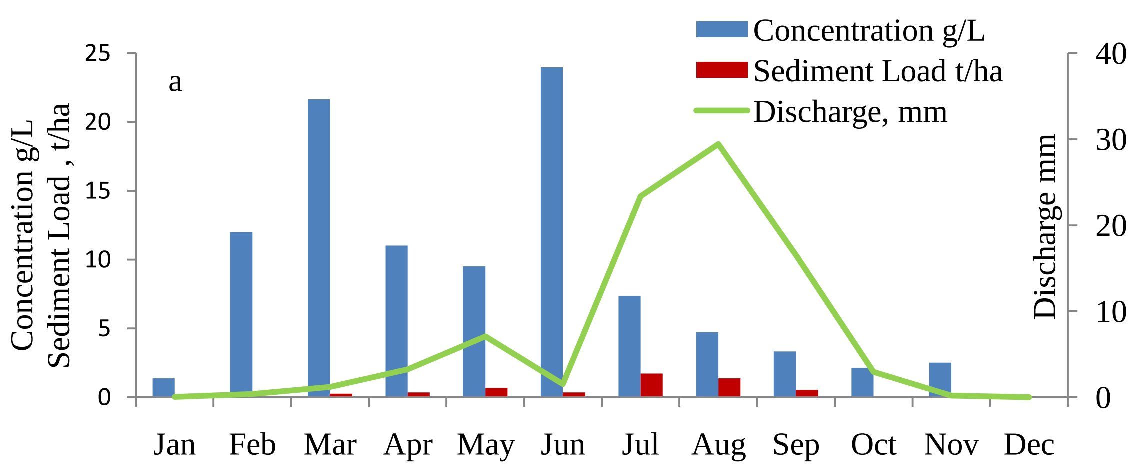
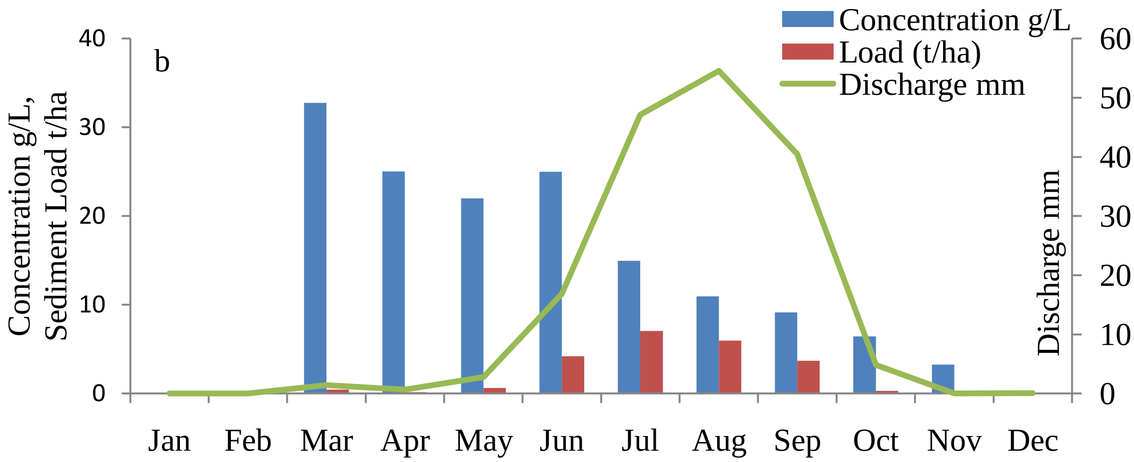
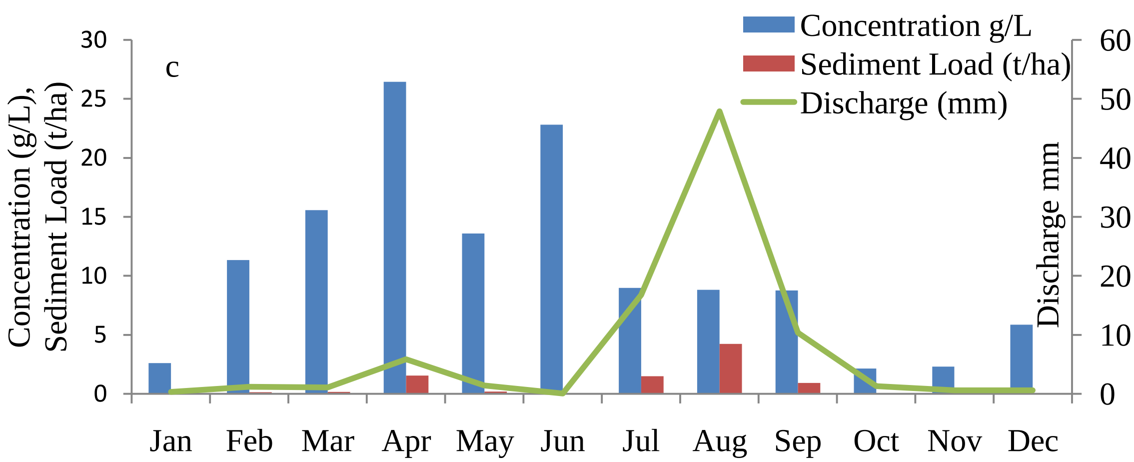


Figure 4: Mean Monthly Sediment Concentration, Sediment Load, Discharge (a) Andit Tid (b) Anjeni (c) Maybar.

Figure 4 (Continued)





A simple SSC-Q relationship could not be confirmed on a biweekly scale since max correlation coefficients did not exceed 0.22 (Figure 2). Biweekly summations were the chosen time scale for further investigation of SSC-Q relationships with stratification for two reasons: (1) to assess the importance of interflow in discharge, as suggested by Lui et al (2008) and (2) to minimize bias caused by the large number of events with low flow and low concentration.

Table 2: Biweekly Sediment Concentration vs. Discharge Power Regression *a*, *b*, R^2 values

Watershed	Figure 5	Group	a	b	R^2
Andit Tid	a	ALL	4.73	0.11	0.05
		P<100	5.05	0.32	0.27
		100<P<300	5.80	0.21	0.08
		300<P<500	9.40	-0.21	0.41
		500<P<700	7.02	-0.048	0.01
		700<P<900	3.14	0.021	0.002
		900<P	3.77	.036	0.01
Anjeni	b	ALL	9.35	.076	0.03
		P<100	16.6	0.395	0.26
		100<P<300	11.4	0.283	0.47
		300<P<500	3.12	0.569	0.64
		500<P<700	5.04	0.251	0.21
		700<P<900	3.43	0.336	0.66
		900<P	4.66	0.17	0.19
Maybar	c	ALL	3.34	0.262	0.22
		P<100	8.37	0.486	0.27
		100<P<300	3.97	0.336	0.31
		300<P<500	1.74	0.513	0.71
		500<P<700	1.64	0.271	0.58
		700<P<900	1.58	0.469	0.54
		900<P	5.07	-0.592	0.94

The Andit Tid watershed demonstrated the most curious results by appearing to display a trend that could not be defined by rating curves. Although exhibiting a strong exponential decay-like visual trend in each of the aforementioned time scales, subdivided concentration data points (Figure 5a), failed to indicate the existence of a strong SSC-Q relationship changing moisture conditions in the catchment.

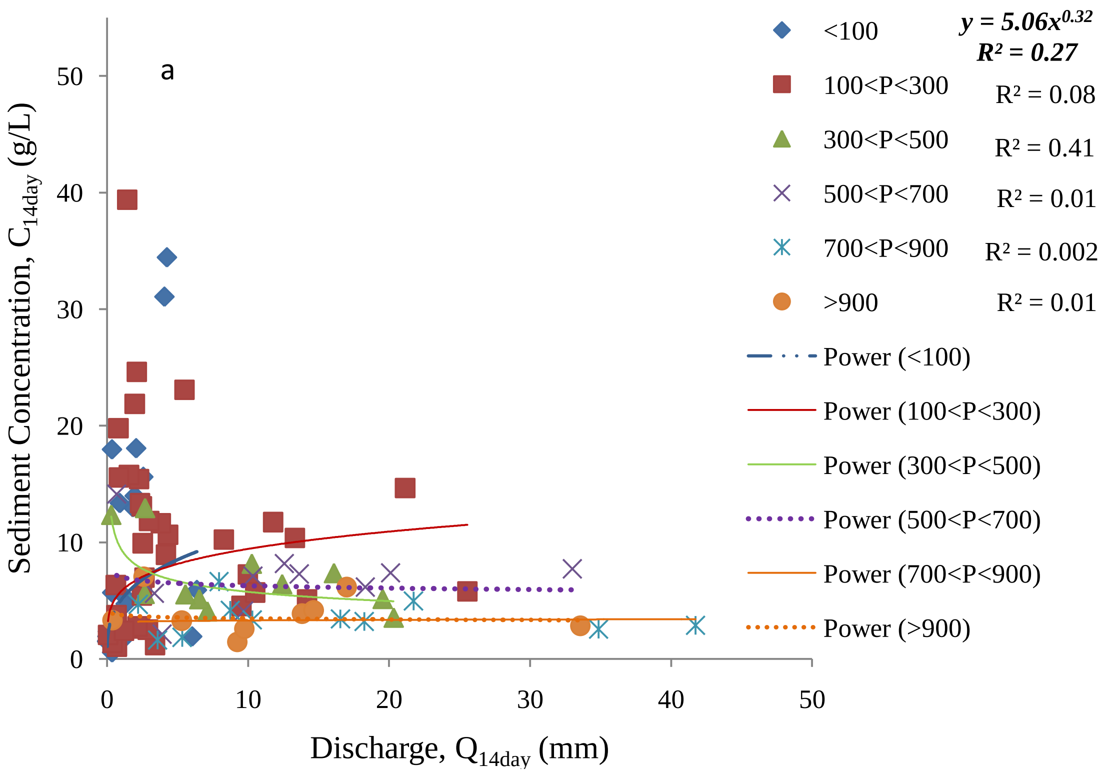
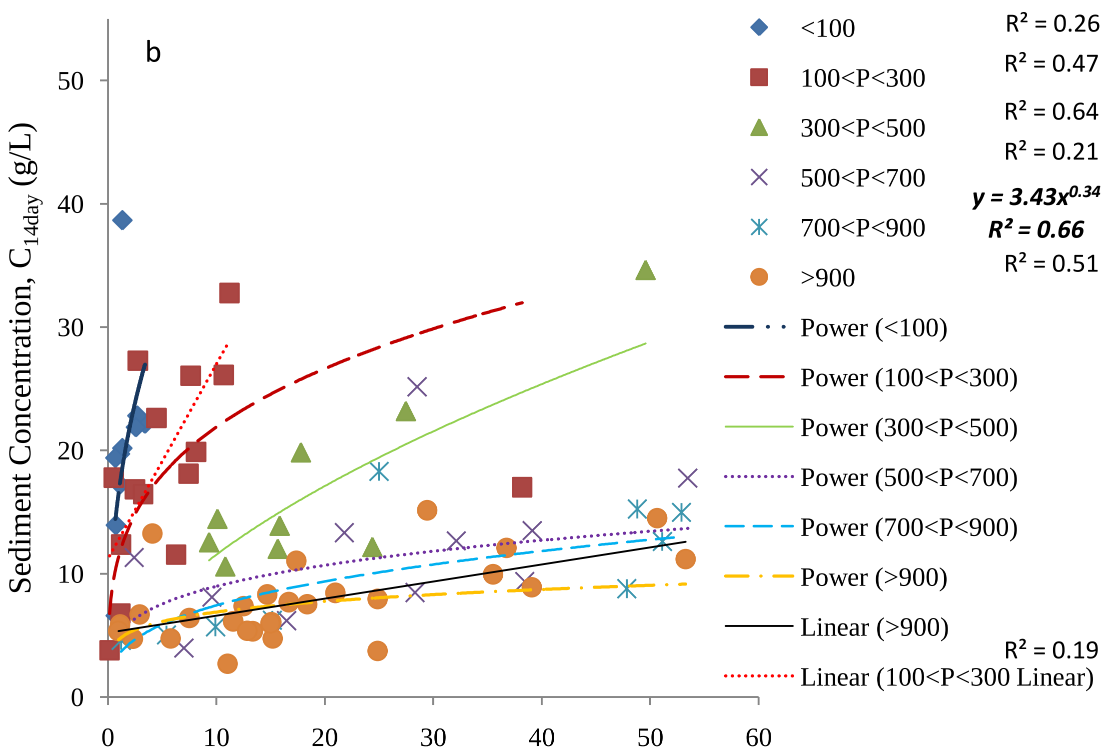
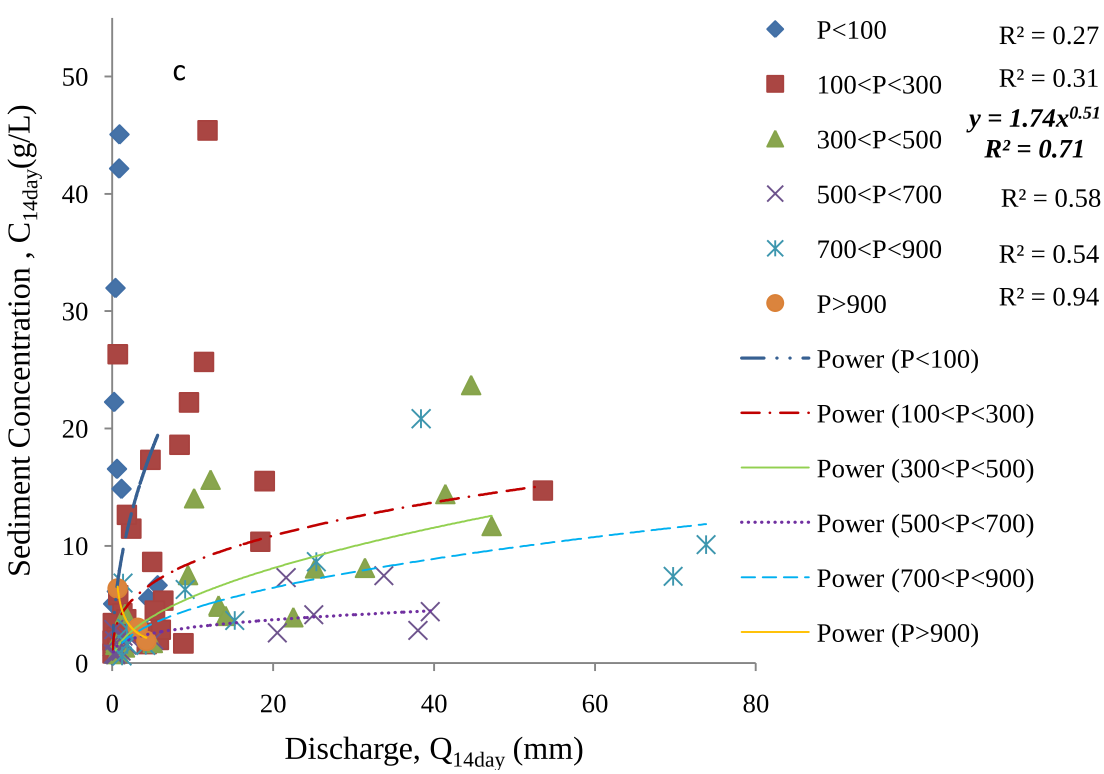


Figure 5: Stratified Biweekly Storm Concentration vs. Discharge (a) Andit Tid, (b) Anjeni, (c) Maybar

Figure 5 (Continued)





The highest R^2 value occurred for the “300<P<500” (0.41) period of the season, in which the relationship shows decreasing sediment concentrations for increasing discharge (Table 2). The lowest correlation coefficient corresponds to the “700<P<900” precipitation range (0.002), which is the period of reasonable correlation for the other watersheds (Anjeni 0.66; Maybar 0.54). Asselman (2000) suggest that flatness (high *a* and low *b* values) and steepness (low *a* and high *b* values in equation 2) of rating curves could indicate shifts between sediment transport regimes from the draining of intensively weathered materials to high eroding power of discharges. Yet, this watershed differs from the German river lowland rivers that Asselman (2000) investigated in that there was not a discernable trend in *a* and *b* values. As a whole, Andit Tid has the least correlation for each soil moisture period. Possible groupings that separate among threshold values of Q as done by diCenzo and Luk (1997) in small subtropical South Chinese catchment were carried out but even weaker agreement was achieved.

The Anjeni watershed has the most scatter for its graphical representations of SSC-Q plots (Figure 2b) for the biweekly time scale and declaring a strong SSC-Q relationship would seem unjustified were it not for the cumulative precipitation grouping. Fortunately, the correlation found in the Anjeni watershed is an improvement compared to the Andit Tid watershed when observations were stratified, (Figure 5b), especially during periods of “300 <P<500” (.64) and “700<P<900” (.66). The period in between exhibits low correlation (0.21) perhaps related to the transition from the month of July values (during which average sediment load peaks) and mid to late August values (during which average discharge peaks) exhibited for the monthly scale (Figure 2b).

Lastly, the Maybar watershed had the best correlation for discharge and sediment concentration when divided into cumulative precipitation groups (Figure5c). Once again, the group of data points within “300<P<500” yielded one of the closest relationships (0.71). Higher correlation is only found for values at which seasonal precipitation reaches higher than 900mm, although more data points would be necessary to confirm the agreement that decreasing concentration would be linked to increasing discharge. Above 500mm of cumulative rainfall, discharge accounts for at least 50 percent of the variation in SSC.

Aggregate graphs were also plotted to compare the SSC-Q relation among the watersheds (Figure 6 a, b, c). Early rainfall periods and late rainfall periods show poor correlation for the power regressions at 0.24 and 0.23, portraying what is noticed for the most part at each of the watersheds. Poor late rainfall SSC-Q correlation for the aggregate graph is likely unbalanced by the very low correlation for Andit Tid. The middle of the season values have the best fit for the power regression (0.46). At each precipitation range the three watersheds are behaving visually similarly, although the range below 300m of cumulative rainfall shows the most scatter. Thus, the decision to divide observations among cumulative rainfall proved fruitful, although sufficient improvement for all ranges did not occur. Using the Kruskal-Wallis test, it can be affirmed that the concentrations are lower during the later part of the season with statistical significance ($p<0.001$). Because sediment supply is often suggested as a determining factor for scatter around and limited success of SSC-Q plots (Glysson 1987, Walling 1977), biweekly and aggregate plots were also generated with sediment yield as the dependent variable. Sediment concentration vs. sediment yield graphs showed better correlation for variations in sediment concentration (Figure A4, A5, Table A1).

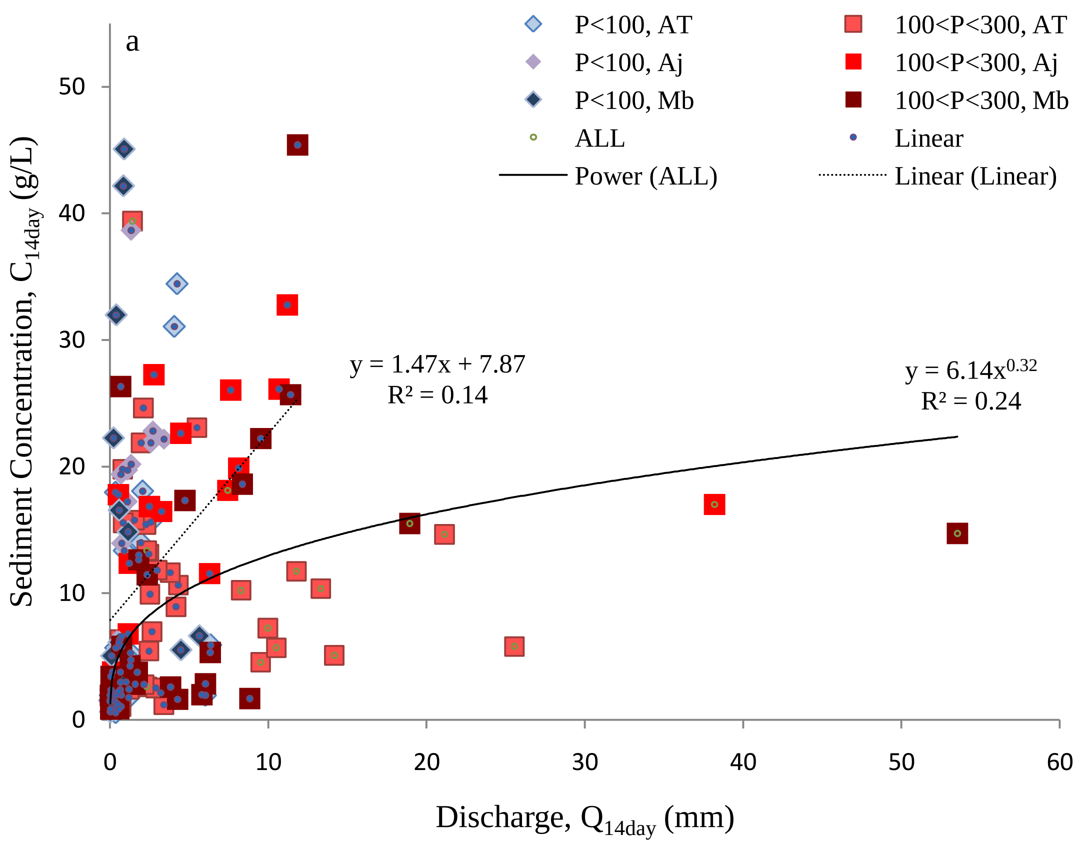
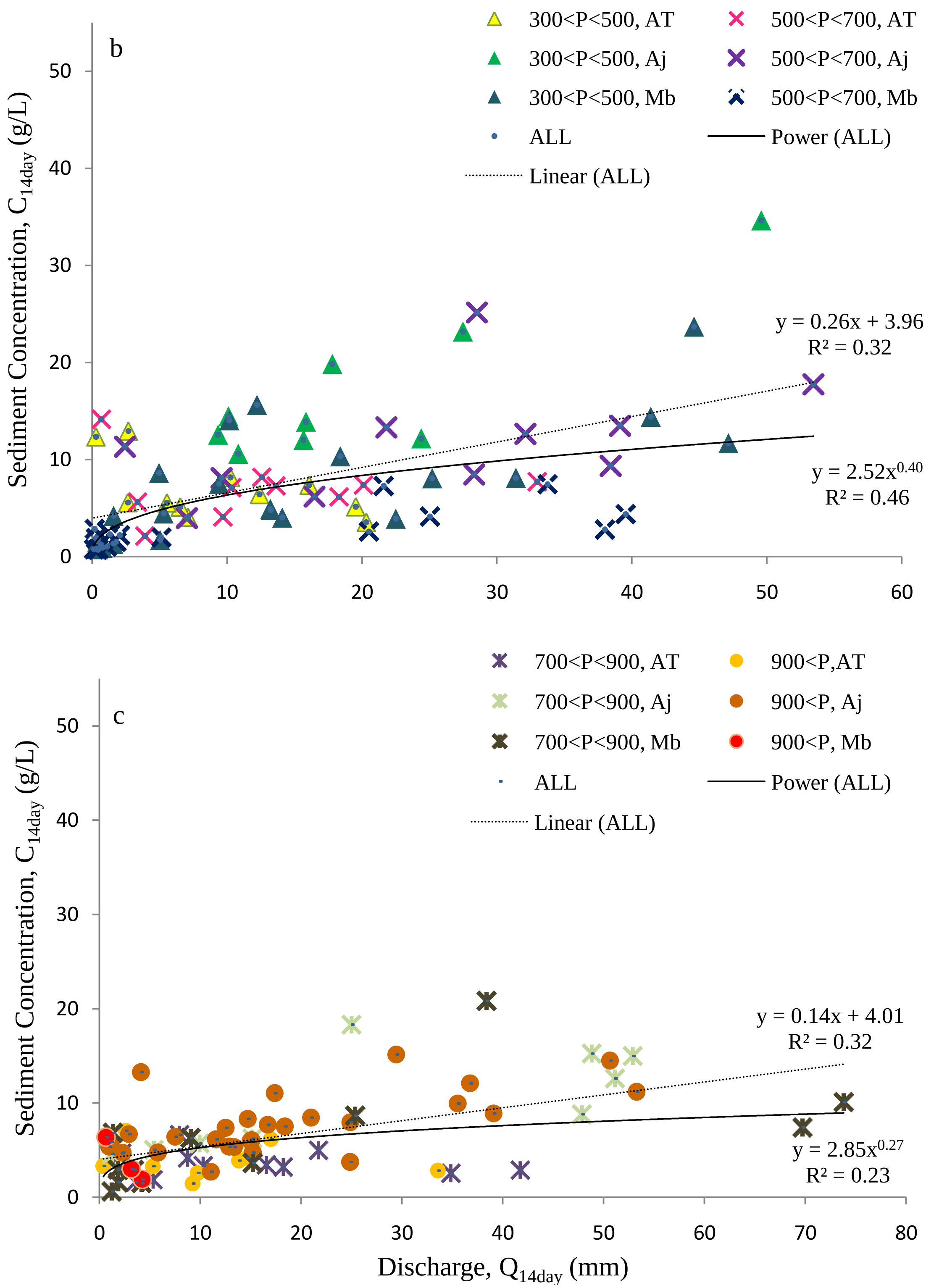


Figure 6. Storm Concentration vs Discharge for (AT) Andit Tid, (Aj) Anjeni, and (Mb) Maybar for (a) P<300mm (b) 300mm<P<700mm (c) P>700mm

Figure 6 (Continued)



4. DISCUSSION

A great deal of variation in stream flow concentration can usually be attributed to changes in river discharge, thus the focus of this study was to determine whether or not this variation could be described through a unique sediment rating curve. The results of this investigation suggest that for all observations a single sediment rating curve, as found to describe some catchments and rivers in Israel (Powell et al 1996, Alexandrov et al 2003) and the U.S. (Putnam and Pope 2003), is unreasonable for the Andit Tid, Anjeni, and Maybar watersheds. Furthermore, the limited improvement found for the stratification of measurements into ranges of cumulative rainfall indicate the limitations of using sediment rating curves to explain variations in suspended sediment concentration. Lastly, these limitations seem to be attributable to the changing sediment supply that is likely dependent on susceptibility to splash erosion, tillage activity and vegetation.

4.1 INITIAL SEDIMENT RATING CURVES

The preliminary graphs representing the transport of sediment out of the catchments display significant scatter making it difficult to say that runoff dilution or wash-off alone are sufficient in explaining the variations in sediment concentration. Greater quantities of base flow and interflow can be expected in the later part of the rainy season (Lui et al 2008), but a consistent dilution effect is not observed for all observations. This inconsistent variation opened the question as to whether the dynamics of the river are very high, leading to river bank erosion as suggested on occasion (SCRP 2000b), or whether the overland flow is still causing increases in sediment concentration that contribute to scatter. This also implied that a combination of these processes or other processes was occurring. Yet, scatter is typical for SSC-Q plots when using all values (Asselman 2000, Walling 1977) and at daily or sub-hourly measurements, hysteretic loops can be contributing to this scatter (Williams 1989). In desert streams in India, no correlation was reported for suspended sediment concentration and runoff (Sharma 1984). As a tentative explanation, Sharma suggested the role of splash erosion and flow velocity on sediment detachment during flow events. Stratification (among rising and falling limbs of hydrographs, seasons, discharge threshold values, or cumulative rainfall) often improves efforts to define rating curves (diCenzo and Luk 1997, Lootens and Lumbu 1986, Walling 1989). In this study, cumulative rainfall was chosen for stratification of observation and compared to the results of rainfall-discharge relationships (Lui et al 2008).

4.2 STRATIFICATION BY CUMULATIVE PRECIPITATION

These subdivisions demonstrate that, within in each group, concentration generally increases with discharge which agrees with most studies in temperate (Asselman 2000), semiarid (Powell et al 1996) and (sub) tropical climates (diCenzo and Luk 1997, Lootens and Lumbu 1986). In dividing the data into the different precipitation ranges, the wash-off process would seem to be the simpler explanation for the variations in sediment concentration. The best correlation at each watershed was usually at the "300mm P<500mm" range. For the smaller watersheds, Anjeni and Maybar, it can be argued to some extent that this is the process responsible to the fluctuations in concentration; more so for the Maybar site than for the Anjeni site. For instance, the wash-off process can account for sediment concentration variation from about 50 percent to 70 percent around or after the middle of the rainy season in the Maybar catchment and about 65 percent for two precipitation ranges in the middle and late part of the season at the Anjeni catchment. These correlation coefficients are quite good and higher than most non-linear regression coefficients for other study locations, including along the Rhine River (Asselman 2000) and a subtropical Chinese catchment studied by diCenzo and Luk (1997). Other suburban tropical basins yield correlation coefficients of 0.74 and 0.78 when decomposed into rising and falling stage data (Lootens and Lumbu 1986). Unfortunately, in these Amhara watersheds good agreement for rating curves was not noted for all decompositions. Several studies in Iran (Sadeghi and Saeidi 2010) and northern Ethiopia (Vanmaercke 2010) suggest that high variability of regression coefficients between SSC and Q data could be affected by factors like sediment availability, rainfall characteristics, and human interference. Using cumulative rainfall precipitation subdivisions improve sediment rating curves for parts of the observations in each watershed, yet this progress is hampered by low correlation for SSC-Q relationships that were also found.

4.3 WATERSHED CHARACTERISTICS AFFECTING FITTING OF SSC-Q RELATIONSHIPS

The Andit Tid site showed the least correlation for all the precipitation ranges. This limited correlation alludes to the previous warnings from Hurni (1985) and Nyssen et al (2004) that soil export via rivers and soil loss from experimental fields are clearly different. Because it is four times larger than the other two sites, there is likely to be less area-specific sediment yield (t ha^{-1} $year^{-1}$) (Nyssen et al 2004), as well as a greater influence of other obstacles to erosion such as vegetative cover. The catchment is also subject to land slides, producing irregular sediment transport. The Andit Tid and Maybar sites experienced reforestation since the early 1980s, whereas Anjeni has experienced deforestation of nearly all 1957 levels of forest (Hurni 2005). This could be a reason that discharges in Anjeni account for a larger portion of sediment concentration variation than the Andit Tid catchment. Furthermore, according to Yohanes (1989), 15 percent of the land in Andit Tid is cultivated with most of the area covered by bushes and perennial grasses, whereas 70 percent (1984-1991) to 90 percent (currently) of the Anjeni catchment is cultivated (Legesse 2009). A large gully can be found in this catchment that contributes to irregular sediment movement. The Maybar site performed the best out of the three sites, which is interesting because it has the least average rainfall and a lesser amount of land (60 percent) that is cultivated (Hurni et al 2005). It is possible that the relatively small size of the catchment, combined with the shallow soils, more equal proportion of cultivated and non-cultivated land, and lower rainfall patterns produced conditions for which discharge was the dominant process in sediment concentration variations. It is also noted that little channel erosion occurs in Maybar. The Maybar site differs in size with Andit Tid, but shares the bimodal rain season pattern. Its size is comparable to the Anjeni watershed, yet contrasts it in receiving lower rainfall distributed during a short and long rainy season.

4.4 OTHER FACTORS CAUSING LACK OF FIT FOR RATING CURVES

Studies in Israel and India that found low correlation between suspended sediment concentrations and discharge point to the spatial and temporal variation in sediment supply in order to explain variations in concentration (Powell et al 1996, Alexandrov et al 2003, Sharma et al 1984). Possible processes that explain supply variation are the exhaustion of readily available soil from the land and vegetative ground cover. Hairsine and Rose (1991) report that during individual storms a protective layer of soil can form to limit detachment of sediment particles and Sander et al (1996) found initial high sediment concentrations have a much greater fraction of fine sediment than later concentration values. In the Ethiopian highlands, an analogously larger scale trend might explain the low correlation for discharge-sediment concentration relationships during parts of the rainy season. During the early rainfall period, agricultural activity is highest in terms of soil disturbance (Zeleke 2001). The beginning of the rain season is when plowing and sowing is prevalent for the rain-fed crops of the highlands. Tillage disturbs the soil structure and produces loose aggregates liable to be carried away by storm runoff. Since 90 percent of the population of the Amhara region lives in the highlands, and 90 percent of the land there is regularly cropped land the possibility for soil loss is very high (Desta 2000). In the Tigray highlands of Ethiopia, Nyssen et al (2000) estimated that about half of the sediment deposited behind newly constructed stone bunds was due to tillage erosion. As more zones become active in contributing runoff (Lui et al 2008), more sources of sediment become available, which could explain why for some of the watersheds SSC-Q relationships have the most scatter during the cumulative precipitation range of “100mm<P<300mm”. After 500mm of cumulative rainfall, Lui et al (2008) show that a consistent ratio of precipitation becomes discharge; this well behaved nature does not translate into a consistent sediment concentration-discharge relationship for all the watersheds. As the soil available for transport is becoming exhausted and vegetation is beginning to provide greater protection, the period following the 500mm rainfall threshold is more likely to follow a simple relationship for suspended sediment dynamics. The precipitation ranges above 500 mm, however, do show less scatter, possibly related to the consistent nature of precipitation discharge relationship. Statistically and visually, higher concentrations are observed for early rainfall periods.

The findings suggest that sediment sources are more important in the fluctuations of sediment concentration. Although this study does not specifically look at sources, studies in these watersheds and other watershed suggest changing sediment supply dynamics interfere with the establishment of rating curves. As the season begins, in the instance of Anjeni, about 77 percent of the lands are in cultivation and typically lie bare with very little vegetation (Gete and Hurni 2001). This means that loose aggregates are prepared by tillage, and furthermore, that there is the greatest exposure to splash erosion which is essential in carrying away fine sediment (Sander 1996). As the season progresses, the sediment supply becomes exhausted in two ways. Overall sources of readily available soil have diminished as the top layer has been washed away leaving the deposited or original soil that can control further detachment (Hairsine and Rose 1991). Also, vegetation cover has increased throughout the watershed as a result of crop growth meaning that susceptibility to splash erosion is reduced and that a better structured soil is likely preventing detachment (Desheermacker 2006). These influences and variable catchment responses for different moisture statuses in the watershed verify that discharge cannot be recommended as excellent indicator for SSC prediction in the Amhara Region of Ethiopia. This finding was also reported by Sadeghi et al (2008), Sharma et al (1986), Alexandrov et al (2003) and thus care should be executed as sediment yield estimates based on sediment rating curve calculations may involve great error (Walling 1977).

5. CONCLUSION

Soil erosion occurs in the Ethiopian highlands in response to the changing land use and heavy rains that characteristically fall within several months. By studying the suspended sediment dynamics at the outlet of three watersheds, the role of storm runoff in determination of concentration was assessed. Initial higher concentrations for low flows with later lower concentration for high flows incited the perception that a dilution effect was occurring as base flow and interflow became more important. Nonetheless, such a relationship could not be verified through various regression analyses. A division of the seasons into moisture conditions (cumulative precipitation ranges) increased the correlation for power regressions of sediment concentration-discharge relationships; however, this improvement occurred inconsistently and insufficiently. The best correlation occurred for periods during “300mm<P<500mm”. Sediment supply and vegetative cover can partially explain why there is variability in correlation coefficients within stratified observations and between catchments. It also may also describe why sediment concentrations are high at the start of the rainy season and lower towards the end of the rainy season. This may show that particular attention should be given to controlling sources of sediment production in the effort to reduce land degradation in the Ethiopian highlands. The variability in goodness of fit for sediment rating curves for the Andit Tid, Anjeni, and Maybar catchments suggest that a simple SSC-Q relationship is not present.

APPENDIX

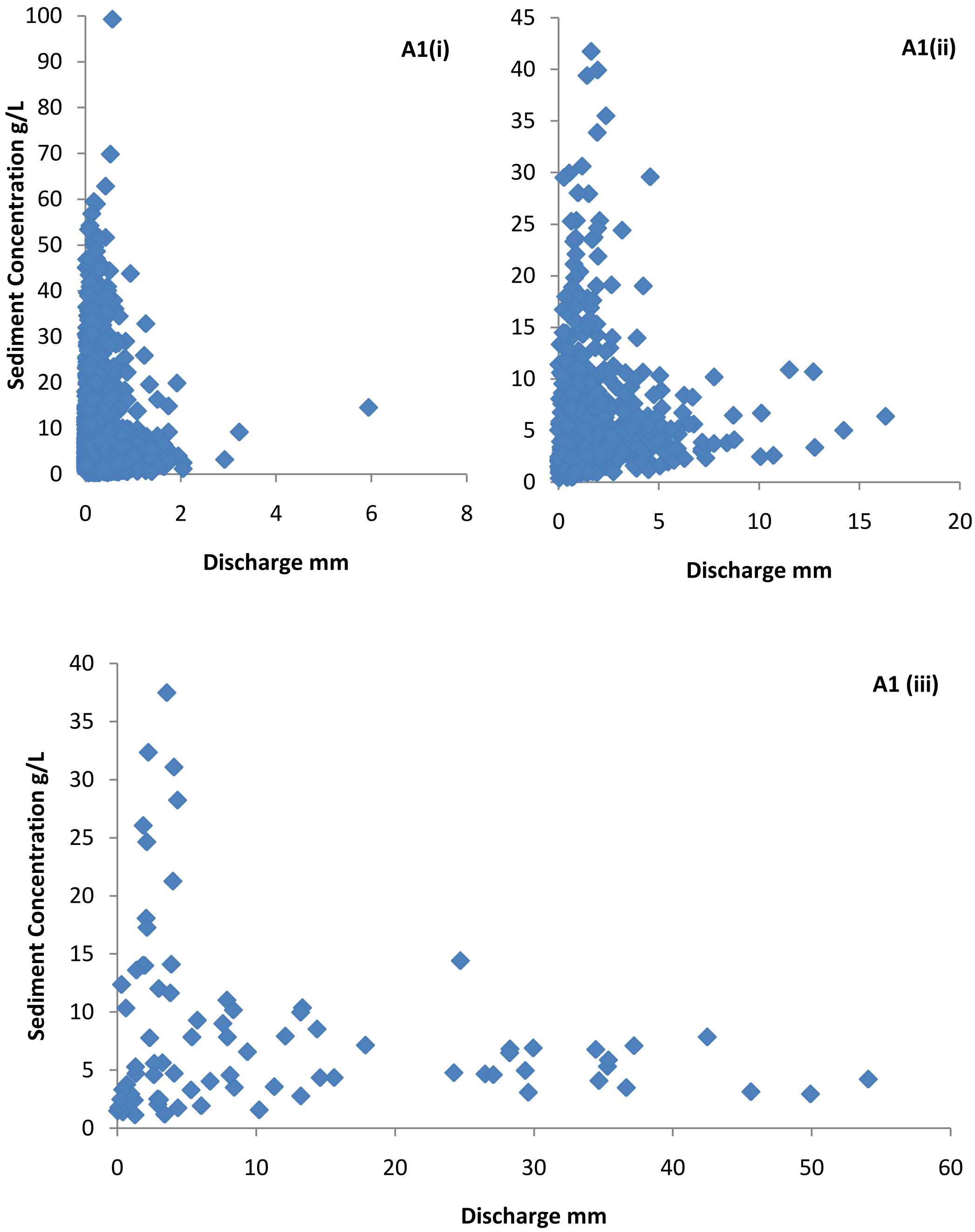


Figure A1: Andit Tid Sediment Concentration vs. Discharge (i) Sub-hourly (ii) Daily (iii) Monthly

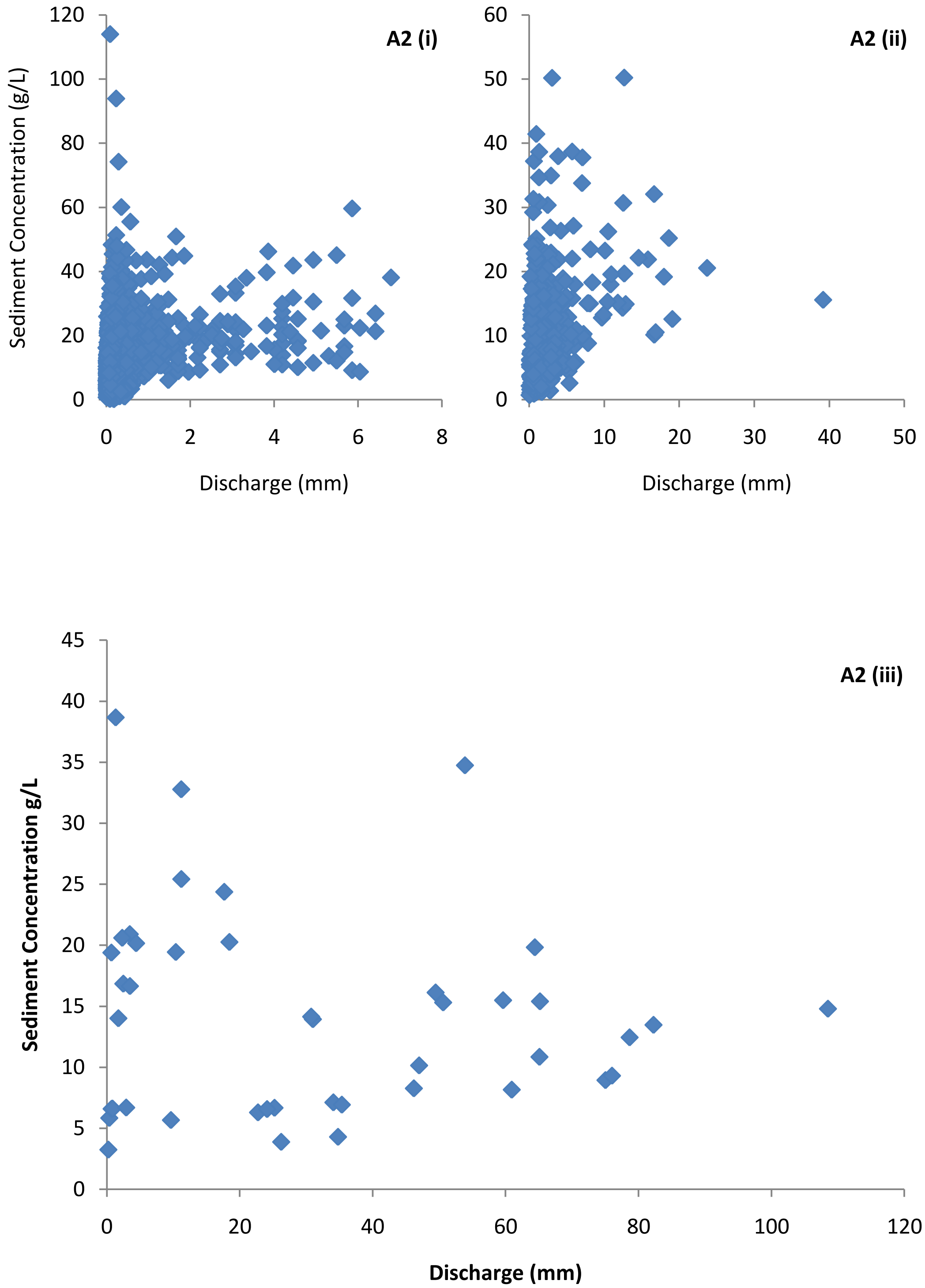


Figure A2: Anjeni Sediment Concentration vs Discharge (i) Sub-hourly (i) Daily (iii) Monthly

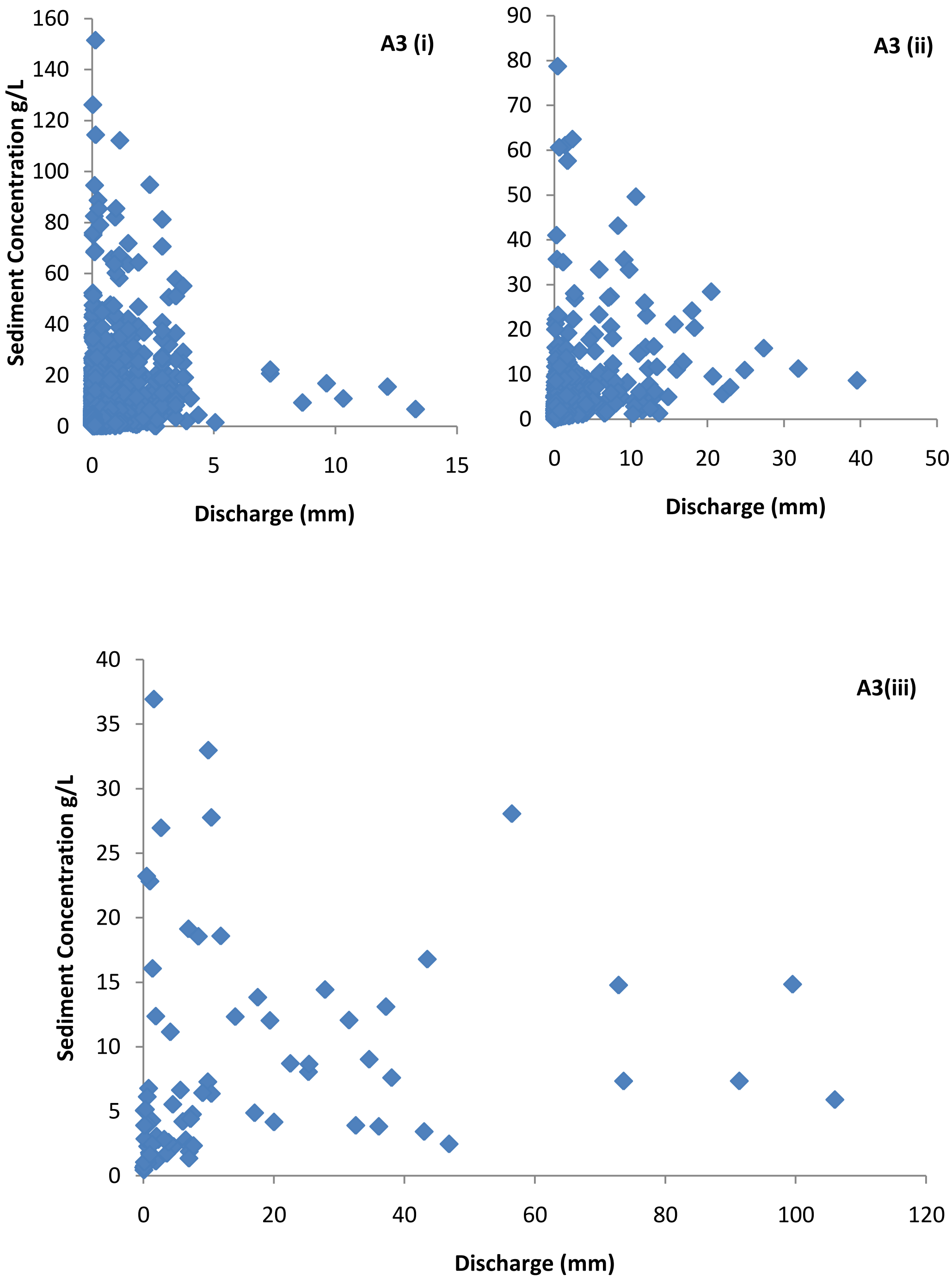


Figure A3: Maybar Sediment Concentration vs Discharge (i) Storm Sub-hourly (ii) Daily (iii) Monthly

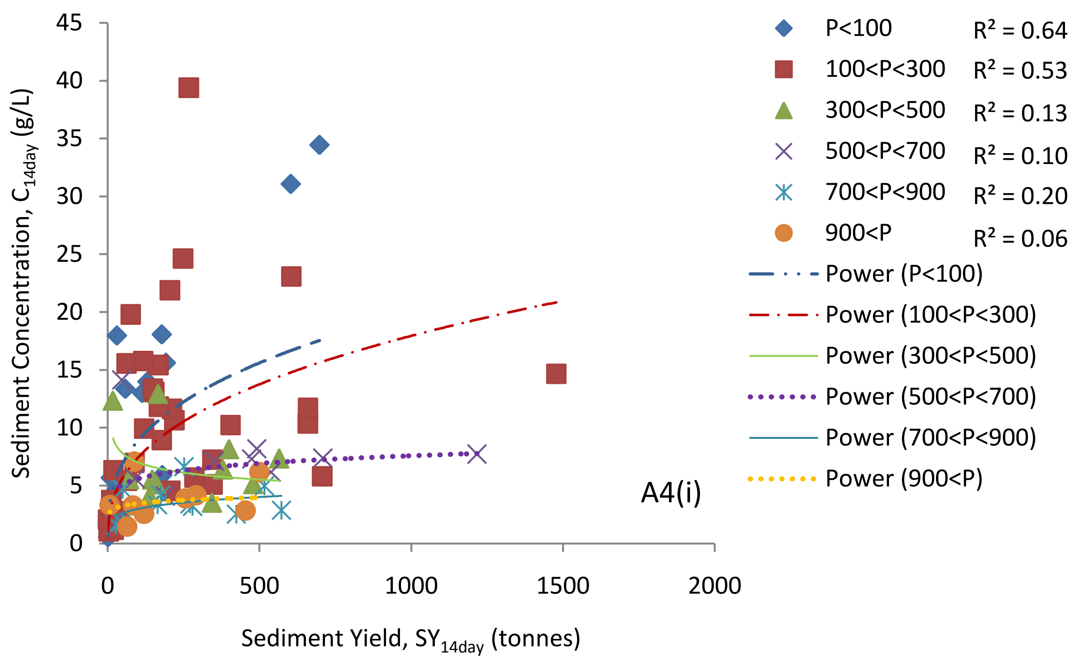
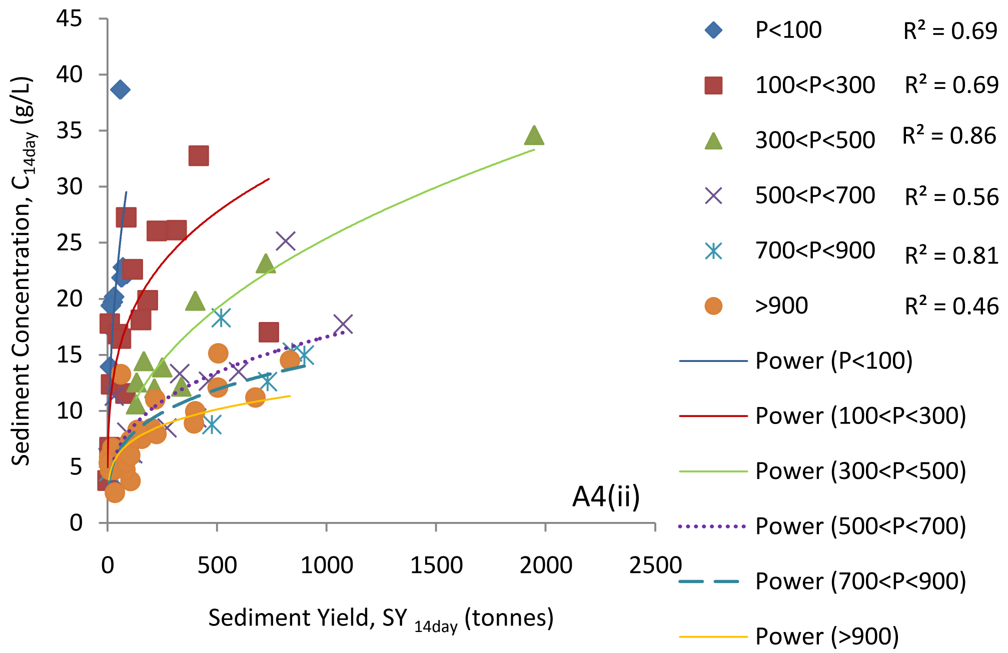
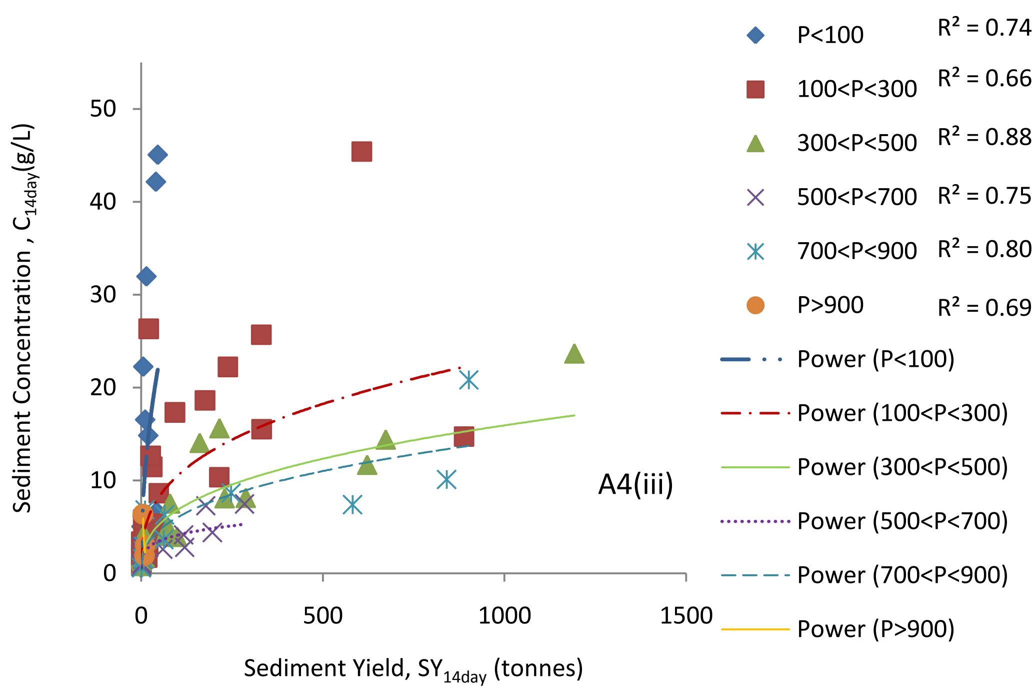


Figure A4: Sediment Concentration vs Sediment Yield with Cumultive Precipitation

(i) Andit Tid (ii) Anjeni (iii) Maybar

Figure A4 (Continued)





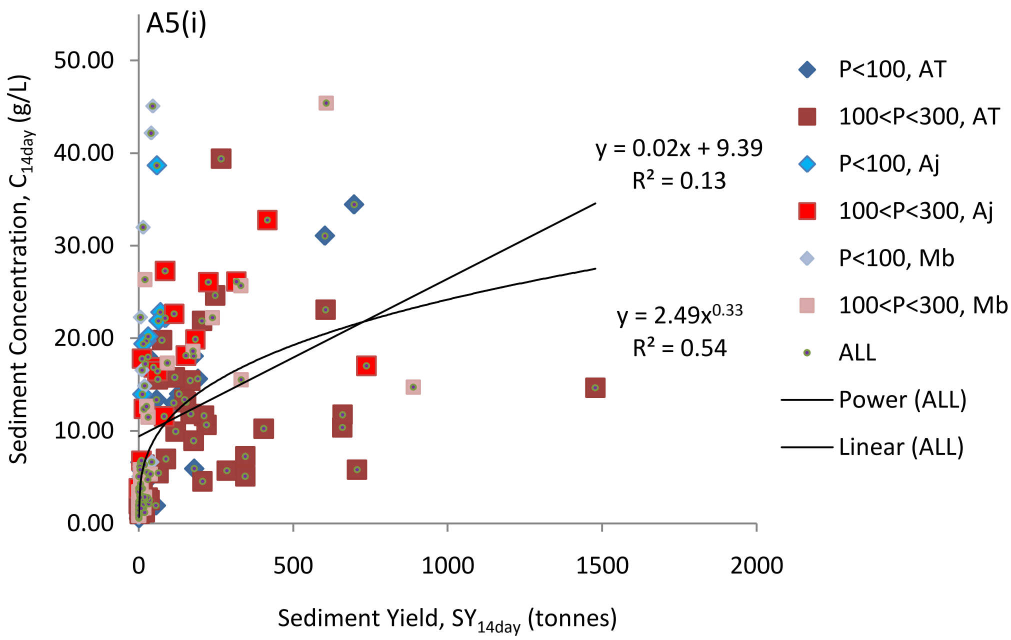
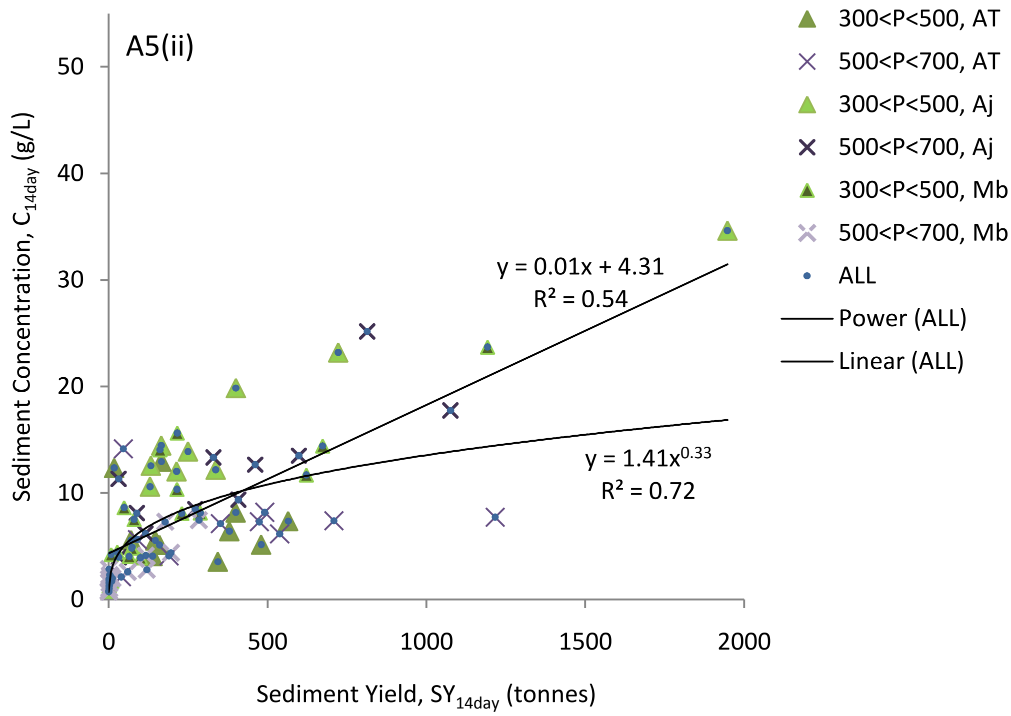


Figure A5:Sediment Concentration vs Sediment Yield all watersheds (i) P<300 (ii) 300<P<700 (iii) P>700

Figure A5 (Continued)



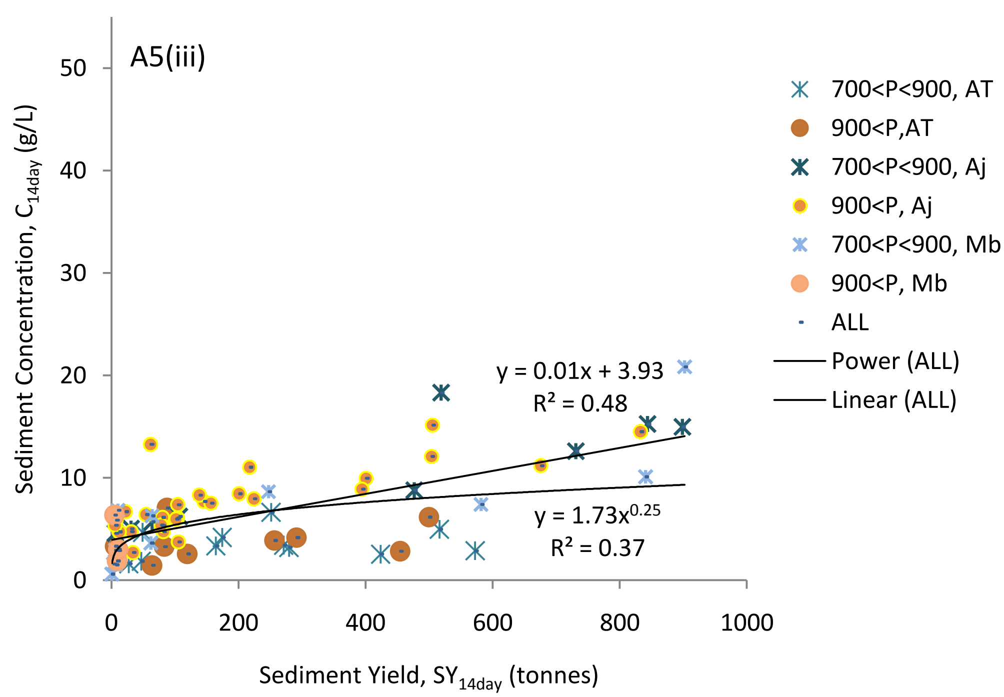


Table A1: Biweekly Sediment Concentration vs Sediment Yield R^2 values

Watershed	Fig A4	R^2 P<100	R^2 100<P<300	R^2 300<P<500	R^2 500<P<700	R^2 700<P<900	R^2 900<P
Andit Tid	i	.64	.53	.13	.10	.20	.062
Anjeni	ii	.69	.70	.86	.56	.81	.46
Maybar	iii	.74	.66	.88	.75	.80	.69

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